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PREFACE

The work described in this report was performed by the Guidance and Control Division of the Jet Propulsion Laboratory.

CONTENTS

ABSTRACT

To investigate cesium plasma parameters that are required for a minimum plasma-loss operation of thermionic converters, a metal-ceramic device equipped with a movable Langmuir probe was constructed. The probe characteristics were examined for four different modes of cesium discharge including: (1) extinguished mode, (2) anode glow mode, (3) ball-of-fire mode, and (4) plasma mode to determine the space potentials and the electron energies in the plasma. The process of cesium ionization that is influenced strongly by the electric potential gradient is being studied to yield a minimum plasma-loss operation.

I. INTRODUCTION

Cesium-filled thermionic energy converters are being considered as candidate electrical energy sources in future spacecraft. The conversion of primary heat energy to usable electrical energy in the converter is accomplished by (1) emitting thermionic electrons from the emitter electrode, (2) transporting these electrons through an interelectrode gap, and (3) collecting these electrons at the collector electrode. Conversion efficiency, which is typically 10%, is influenced by, among other things, transport losses in the interelectrode gap. These losses occur as (1) electron scattering and (2) plasma voltage drop. Because of the scattering, approximately 30% of emitted electrons do not reach the collector, and because of plasma voltage drop, nearly 50% of the available voltage output is lost in a converter operating in an ignited mode. However, to date, no positive attempts have been made for operating a converter in an unignited mode, although it would have smaller plasma losses if the optimum plasma parameter could be determined. An additional advantage of operating a converter in such a mode is that the increase in the output voltage and the decrease in the output current would make the power conditioner more efficient and lighter in weight. One approach to achieve an efficient unignited mode is to reduce the cesium pressure and to depend upon cesium ions being generated at the electrodes for space charge neutralization. To achieve the above goal, an investigation of an unignited mode has been initiated to determine diode parameters that yield minimum plasma losses. The investigation includes (1) ionization mechanisms in the collector sheath and (2) space charge neutralization factors in an unignited mode as well as ignited modes.

The cesium pressure reported herein was limited such that the electron mean free path was larger than the interelectrode gap; higher pressure cases will be presented in subsequent reports. As the diode current increases, the discharge mode takes four different forms (Ref. 1): (1) extinguished mode, (2) anode glow mode, (3) ball-of-fire mode, and (4) plasma mode. Modes (3) and (4) are in the category of ignited mode. It was determined that a major part of the voltage drop always occurred at the edge of the plasma whenever a glow was visible in the interelectrode gap. It was also determined that the space charge near the emitter was fully neutralized by those ions that were generated in the anode glow region when the diode current increased to the transition point into the ball-of-fire mode. Measured potential profiles and the electron energy distributions in various modes are also discussed in this report.

II. LANGMUIR PROBE TUBE

The Langmuir probe tube that was used in this investigation, was similar to R. Bullis' (Ref. 2), is a simulated thermionic converter having a plane parallel electrode geometry. The interelectrode gap (≈5.2 mm) of the tube is made large enough to facilitate the investigation of plasma properties by a Langmuir probe that is movable through a hole in the center of the collector. Materials for the emitter, collector, collector guard ring and the probe are tantalum and the collector that defines the active area of the diode is 1.27 cm^2. These electrodes were assembled into a 3.81 cm diameter stainless steel tube. Figures 1 and 2 show exploded and assembled views of the Langmuir probe tube. The emitter on the left has a separate vacuum compartment for the electron-bombarding mechanism and the collector on the right has a guard ring and the movable probe, the details of which are shown in Fig. 3. The probe is mounted on a stainless steel bellows so that it can be moved axially through a hole in the collector with a micrometer screw mechanism. The active surface of the probe is parallel with the diode electrodes and is circular with a diameter of 1 mm. The cylindrical surface of the probe is electrically insulated from the plasma by a layer of tantalum oxide that was formed by heating a tantalum wire in in an oxidizing atmosphere. This type of insulation is very satisfactory since it does not appreciably disturb the plasma nor the space in the immediate vicinity of the active surface of the probe because its thickness (≈0.05 mm) is considerably smaller than the probe diameter. Hairline cracks in the oxide, as shown in Fig. 4, were small compared with the mean free path of electrons and therefore a porosity of the oxide would not contribute to the active area of the probe in the plasma.

The emitter button having a diameter of 1.96 cm was electron-beam welded onto a tantalum cylinder having a wall thickness of 0.038 cm and a length of 5.0 cm. The assembly was mounted on a "double" flange so that the electron bombarder was in a vacuum compartment which was separated from the cesium-filled compartment of the diode. Electrically the diode emitter was at the same potential as the tube envelope because of the construction. Although the tantalum cylinder was used to limit the heat conduction from the emitter button up to the flange, it was found that a spurious bombarding of the cylinder wall necessitated an addition of a heat shield fitted inside of the cylinder.

The cesium reservoir was located in a copper tubulation that was adequately isolated from the diode itself. During operation, the reservoir temperature was raised to a desired value by raising the temperature of the tube envelope that was kept in a thermal blanket; the temperatures of the tube wall were always higher than the reservoir by approximately 50°K.

A sapphire window was provided for: (1) the measurement of emitter temperatures at the blackbody hole, (2) visual observations of the location of the probe tip, (3) the observation of the plasma in the interelectrode gap.

III. EXPERIMENTS AND RESULTS

The schematic diagram, see Figure 5, for obtaining the probe characteristics consists of two electric circuits: (1) the tube circuit for driving the Langmuir tube as a cesium diode, and (2) the probe circuit for measuring the probe current flowing in the probe-anode circuit through a variable probe bias. The probe characteristics were displayed on an X - Y recorder as the bias was swept so that the potential of the probe was varied between -6 volts and +1 volt with respect to that of the collector. The probe characteristics were subsequently analyzed to determine the space potentials and the electron energy diagrams. During the measurements, the emitter temperatures were determined with an accuracy of better than 20°K by an optical pyrometer at the blackbody hole in the emitter. The cesium reservoir temperatures were determined by a chromel-alumel thermocouple that was attached to the reservoir. All critical values were measured with a 6-digit digital voltmeter.

The location of the probe tip was determined by noting the turns of the micrometer screw with respect to the reference location. The reference location was when the probe tip was coplanar with the collector. The quantity "d" in the probe data for the probe location is given in turns of the screw and one turn is equivalent to 1.06 mm from the collector.

In this report, the results are presented only for a case in which the emitter temperature T_E was 1123°K and the cesium reservoir temperature T_R was 405 ±2°K.

Under these operating conditions, the theoretical emitter work function was $2.4^{+0}_{-0.2}$ eV according to Rasor-Warner (Ref. 3), the estimated collector work function was 1.8 ± 0.1 eV; the electron mean free path was approximately 1.0 cm, and the ion-richness ratio (Saha-Langmuir ion current density/Richardson electron current density) was 2.61×10^{-6}. Therefore, the tube was operating in highly electron-rich and nearly collision-free condition when the volt-ampere curves (Fig. 6) showing both the unignited and the ignited mode were obtained. The unignited mode has three sub-modes, i.e., an extinguished mode, an apparent saturation mode, and an anode glow mode. Also, the ignited mode has two sub-modes, i.e., a ball-of-fire mode and the plasma mode according to the characteristics of cesium discharge. To investigate the process of cesium ion generation and the potential profiles in the diode, the electrical properties of the diode and the cesium plasmas in the interelectrode space were examined for all modes of diode operation.

Typical probe characteristics in four modes, i.e., extinguished, anode glow, ball-of-fire and the plasma mode are shown in Figs. 7 through 10. Each family of probe characteristics represents relationships between the probe current and the probe voltage with respect to the collector voltage as the probe moved across the interelectrode gap from the collector at d = 0 to the emitter at d ≃ 5. As seen in the schematic diagram (Fig. 5), the positive values for the probe current mean that the probe is collecting electrons from the space and the negative values indicate that the probe is collecting ions and/or emitting electrons. According to the Saha-Langmuir equation that describes the ion emission at an electrode, the ion emission from the emitter of the Langmuir probe tube under investigation, was found to be at least two orders of magnitude smaller than that measured in the negative-current quadrant of the probe characteristics. Since in the extinguished mode, no ions that would contribute to the negative probe current should be generated in the interelectrode space, the negative currents in the probe characteristics must be equal to the currents generated by surface-born ions which were negligible according to the previous calculation. Therefore, it was concluded that the negative currents in the extinguished mode are the thermionic current from the probe tip which had a temperature of approximately 700°K and a work function of 1.8 eV. The negative currents in excess of these values found in other modes should be the saturated ion current originating in the interelectrode gap.

From these probe characteristics, the potentials in the interelectrode space with respect to the potential of the anode were determined. Since the tube was operating in essentially collision-less regime, the space potential was obtained by assuming a negligible random current. With this assumption, the space potential can be determined at each probe position by finding a voltage at which the probe current equals the short-circuit current at d = 0. In other words, the current when the probe is coplanar and short-circuited with the collector, is assumed to flow through any imaginary plane at d when the probe potential agrees with that of the space. Therefore, the procedure for determining the space potential is (1) finding the short circuit current as an intersect between the probe curve for d = 0 and the ordinate (V = 0), (2) drawing a constant current line passing this current, and (3) reading voltages at intersects between probe curved for desired d and this line. A procedure that is conventionally used for determining the plasma potential by finding the knee of the probe characteristic (Ref. 4) was not employed, since the probe was not in a collision-dominated plasma. In fact, the plasma parameters in this tube were not in the range of validity for the probe (Ref. 5) to be used as a conventional probe except in the ignited mode. In the unignited mode, the particle mean free path was approximately 10 mm, the Debye length at the emitter was 0.1 mm, whereas in the ignited mode, the Debye length at the emitter was reduced to approximately 0.012 mm. The probe radius was 1 mm in both cases.

The space potentials being determined with an aforementioned method are plotted in Fig. 11 as a function of the interelectrode distance measured from the collector for four different modes. All curves converge to the origin where the probe potential should coincide with that of the collector which is at the zero reference potential. To gain further insight into the process of ionization that depends on the space potential, the electrode work functions were incorporated into the probe potential in Fig. 12 and Fig. 13. Emitter work functions were calculated from the Richardson equation for each observed current, therefore they are the surface barrier functions that are influenced by the space charge at the emitter. For example, the barrier function (labeled as emitter work function in the figure) was 2.12 eV in the plasma mode although the Rasor-Warner calculation showed that the work function was $2.4^{+0}_{-0.2}$ eV for the tantalum emitter. An apparent reduction of the work function may be due to the Schottky effect. The collector work function was estimated to be 1.8 ± 0.1 eV by assuming that the cesium coverage was nearly unity.

The Fig. 12 for the plasma mode shows that a high-field region, i.e., an emitter sheath, formed adjacent to the emitter where a potential drop of approximately 1.5 volts occurred. The thickness of the sheath was such that (0.1 mm) the precise determination of the space potential could not be obtained. A photographic record of the interelectrode space in the plasma mode (Fig. 14) showed that a thin dark space having a dimension of the sheath existed adjacent to the emitter. In the anode glow mode, a large potential drop of approximately 5 volts occurred in the space closer to the collector at the edge of the visible anode glow. This potential drop which will be a subject of further investigation is expected to become smaller at increased operating temperatures. In any event, the potential drops in both modes are primarily responsible for the cesium ionization. Another interesting mode, the ball-of-fire mode, is shown in a photograph, Fig. 15. The figure shows the interelectrode space being viewed through a sapphire window that is bordered by a blurred circle. Various objects in this photograph can be identified in a schematic drawing, Fig. 16, except for the plasma and the probe. The quartz cylinder which insulates the collector and its support from the tube envelope has a half-moon shaped cut-out toward the front to allow a clear view of the collector surface and the probe. The well-formed fire ball comes as close as 0.2 mm to the emitter. In the anode glow mode (not shown) the glow of a thickness 1 mm appears on the collector. Experimental findings of the potential profile in the anode glow mode support the analysis in cesium breakdown published elsewhere (Refs. 6 and 7). Also, the general characteristics and the potential profiles are in agreement with those in a cesium thermionic diode (Ref. 8) and in a hot cathode arc (Ref. 9).

To gain some insight about electron energies in the interelectrode space, an electron current equal to the sum of the negative and the positive currents in the linear probe characteristics (Figs. 7-10) is plotted as a function of the probe potential in a semilog form in Figs. 17 through 20. The curves in the plasma mode show well-defined slopes indicating that the electron temperature can be assigned. The temperature increase from 12,600°K near the emitter (d = 4) to 19,200°K near the collector (d = 0) indicating that the cesium plasma at this low pressure (0.0030 torr) is not in equilibrium throughout the space, but is influenced by a finite electric field intensity (3 volts/cm) that accelerates electrons toward the collector. The curves in the ball-of-fire mode show two energy groups one of which has temperatures characteristic of the plasma and the other has temperatures characteristic of the emitted electrons. In the anode glow mode, electrons are not randomized so that the electron temperature cannot be assigned, but there is an indication that the highly energetic group plus the low energy group coexist near the collector where the anode glow forms. In the extinguished mode, the low-energy electrons having characteristic temperature of 2,000°K dominate the electron energy groups, and the general shape of the characteristics is quite similar to that of volt-ampere curves of a variable-gap diode being operated in an unignited mode. Typical curves from JPL SPS, 37-54, Vol. III, 70-73, are duplicated in Fig. 21.

The similarities between those curves and the probe characteristics are not surprising since the probe in the Langmuir tube would be equivalent to the collector in the variable-gap diode. Note, however, that the "avalanche" region near the breakdown shown in Fig. 21 is not apparent in the probe characteristics since the probe potential was not raised much past zero volts.

IV. CONCLUSION

A device that simulates a thermionic converter and also provides cesium plasma data called the Langmuir probe tube has been successfully operated at a low cesium temperature of 405°K. The Langmuir-type probe that moves axially from the collector to the emitter in the interelectrode gap through a hole at the center of the collector, provides the probe characteristics as a function of the location of the probe. The probe is insulated except at its tip, from the plasma with a tantalum oxide that was formed directly over the probe wire. The probe characteristics were obtained for four different modes of the tube operation including (1) extinguished mode, (2) anode glow mode, (3) ball-of-fire mode, and (4) plasma mode. These characteristics were correlated with the visual observation of the interelectrode space and the cesium discharge. The extinguished mode exhibited probe characteristics similar to those in a variable gap thermionic converter operating at low temperatures in a pre-ignition condition. In this mode, a large electric field existed at the edge of the glow as was expected. Electrons near the collector where the glow is located were composed of a high velocity group that was accelerated through the field, and a low energy group that had lost energy on ionizing cesium atoms. The ball-of-fire and the plasma mode exhibited the emitter sheath formation and a plasma that had a characteristic electron temperature at approximately 15,000°K. However, the ball-of-fire mode differed from the plasma mode, in that there were low energy electrons that originated from the emitter. The electron temperature of 15,000°K in the plasma mode is more typical in rare gas discharges than in cesium plasma, but this value is reasonable if one considers that the electron mean path is larger than the interelectrode gap such that a considerably higher temperature would be required to sustain the plasma in this tube. Low energy electrons found in the extinguished mode and in the ball-of-fire mode, had an equivalent electron temperature of approximately 2000°K which was slightly less than twice the emitter temperature. This fact is in satisfactory agreement with temperatures in conventional thermionic converters.

The theory on cesium breakdown was verified with respect to the pre-breakdown potential profile using the probe measurements. Currently the probe measurements in the Langmuir probe tube are being extended to cover cases where the electron mean free path is smaller than the interelectrode gap to provide a comprehensive investigation of cesium ionization mechanisms in thermionic converters. At elevated operating temperatures, an anode sheath drop that is smaller than those described herein and that is favorable for operating a converter in an unignited mode should be obtainable.

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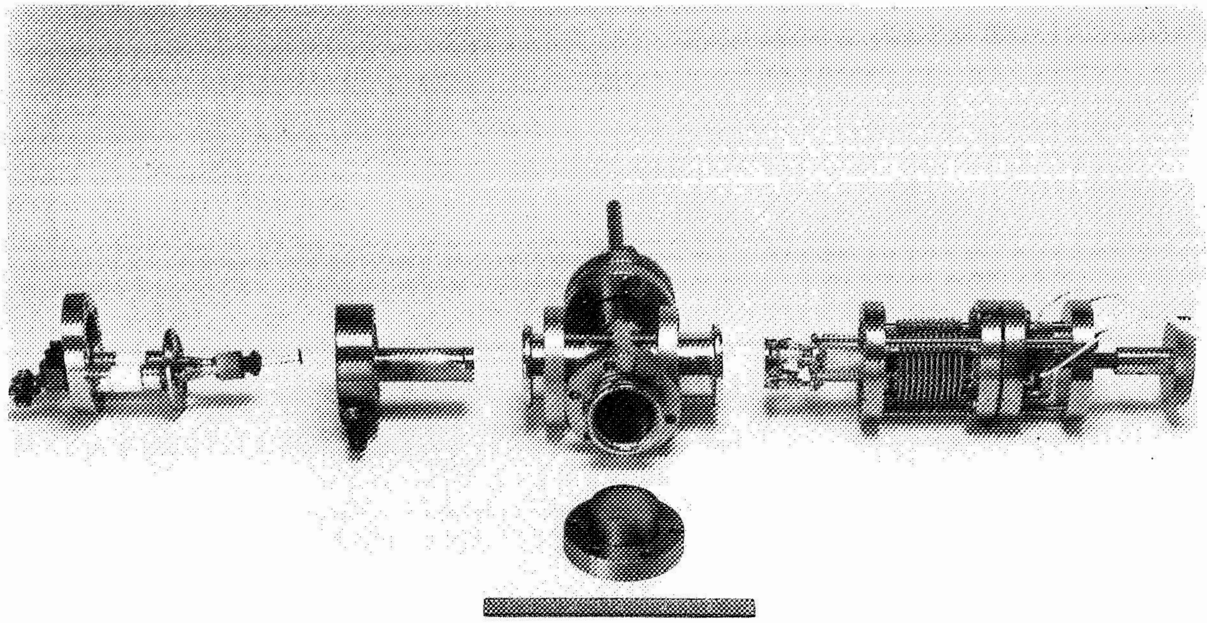

Fig. 1. Exploded View of Langmuir Probe Tube

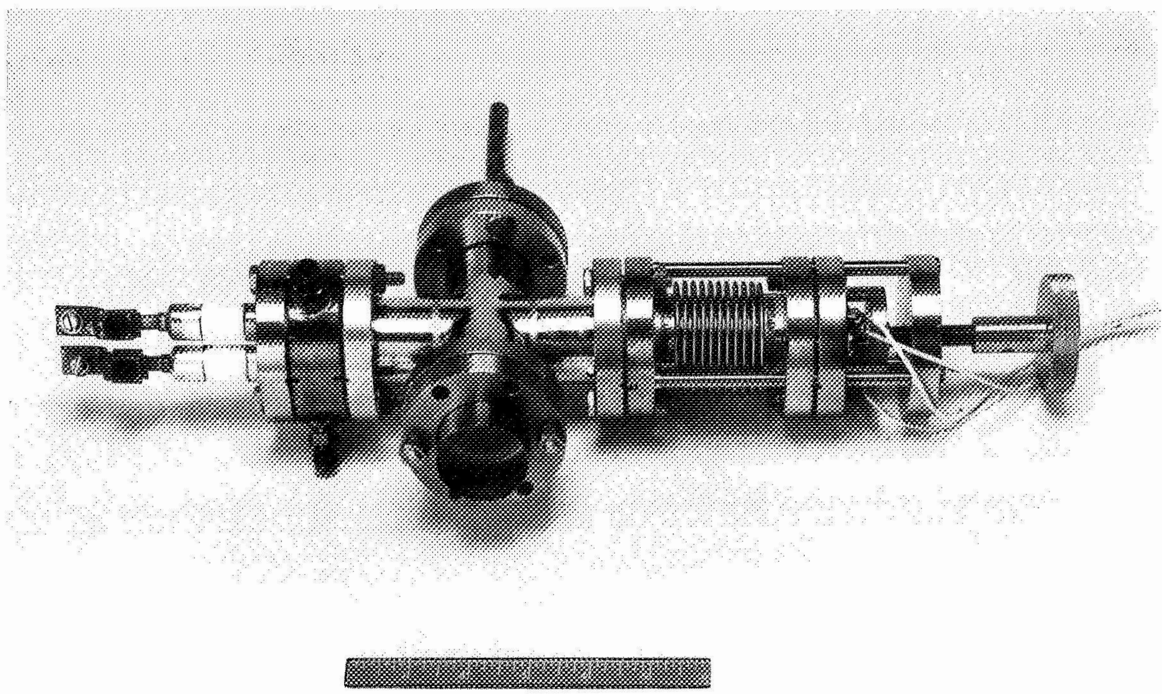

Fig. 2. Assembled View of Langmuir Probe Tube

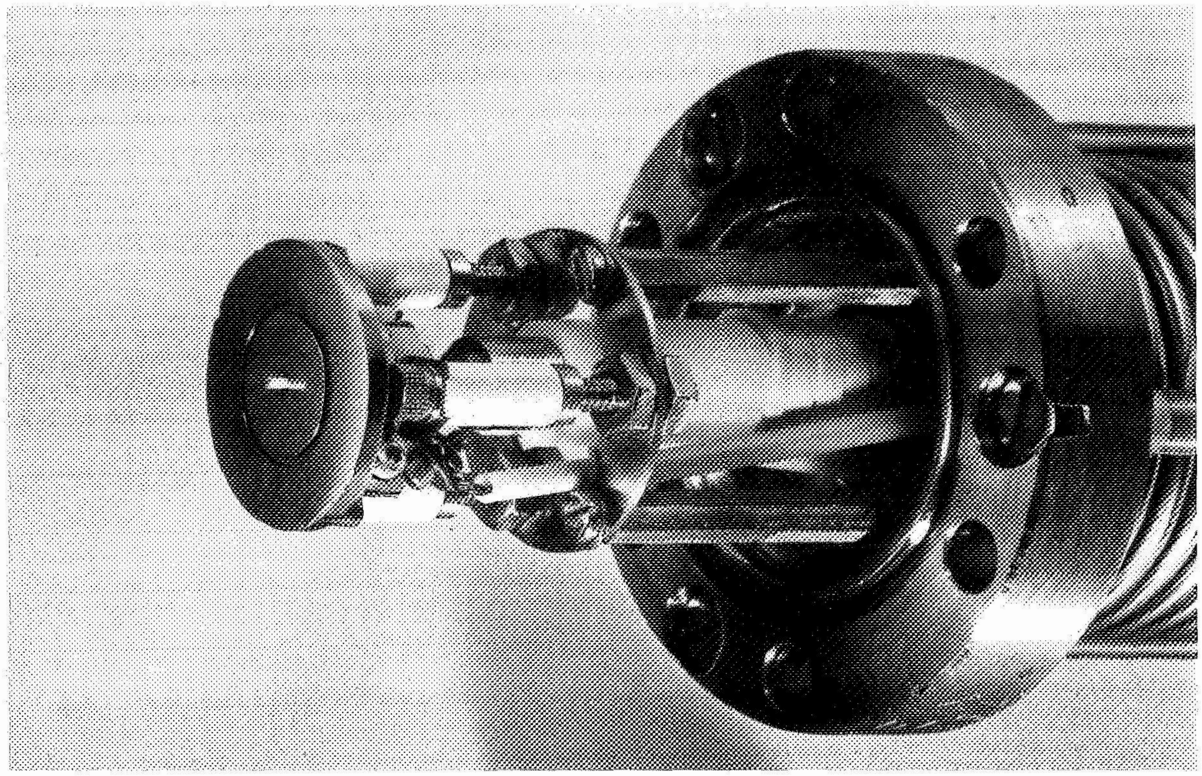

Fig. 3. Collector-Probe Detail

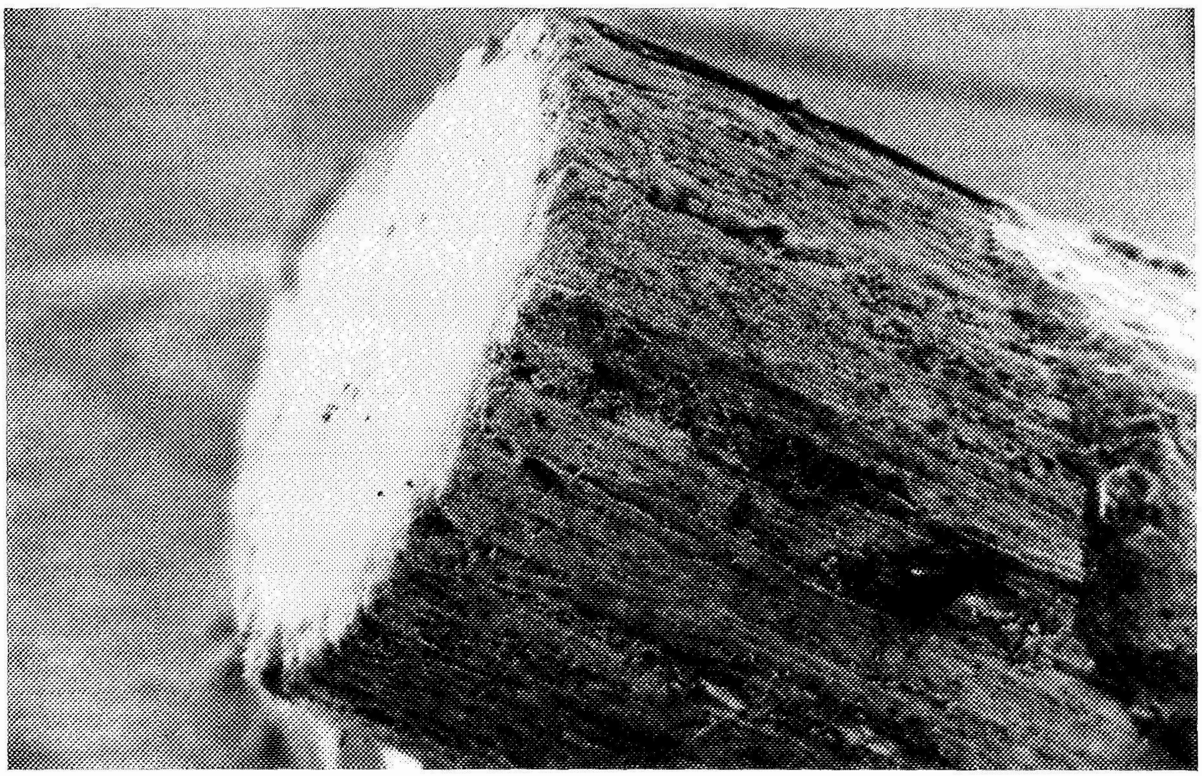

Fig. 4. Scanning Electron-Microscope Picture of a Probe Tip

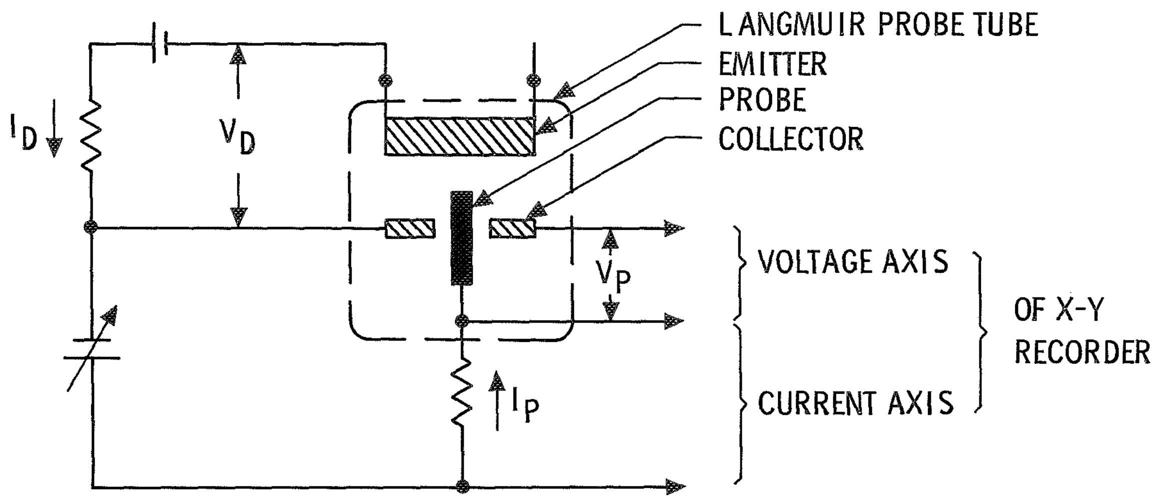

Fig. 5. Schematic Circuit Diagram

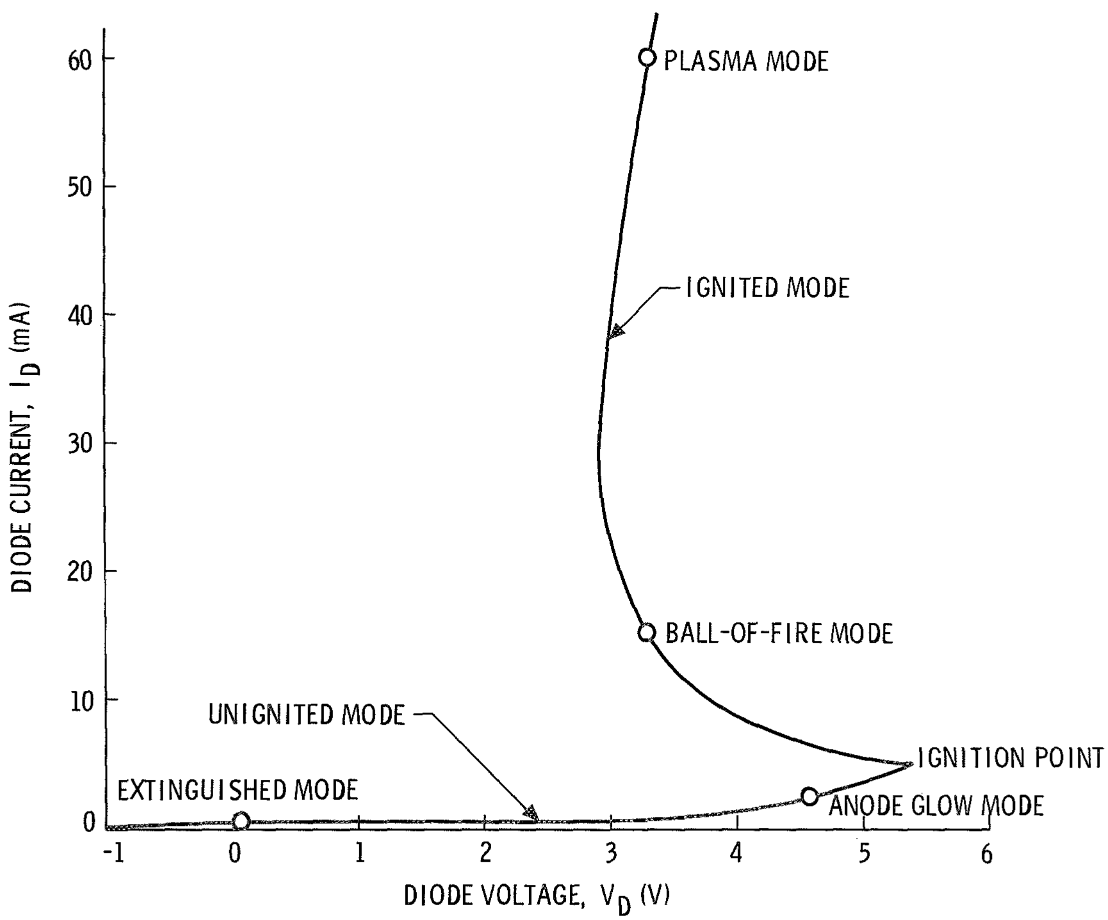

Fig. 6. Tube Volt-Ampere Characteristics at T_E = 1123°K, T_R = 405°K

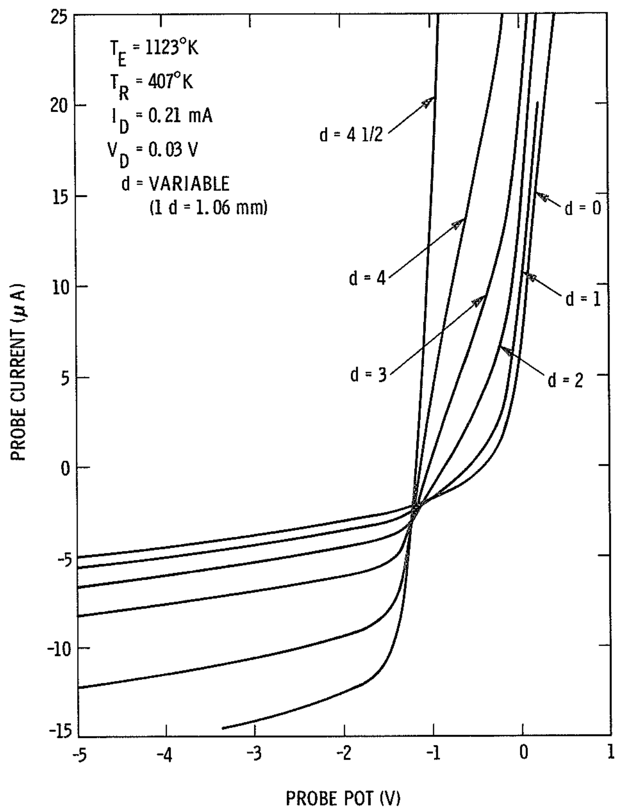

Fig. 7. Probe Characteristics, Extinguished Mode

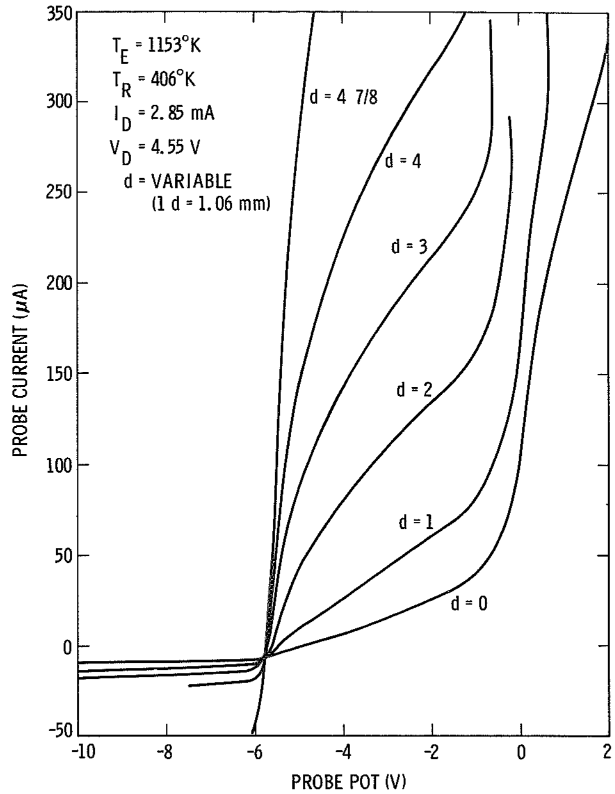

Fig. 8. Probe Characteristics, Anode Glow Mode

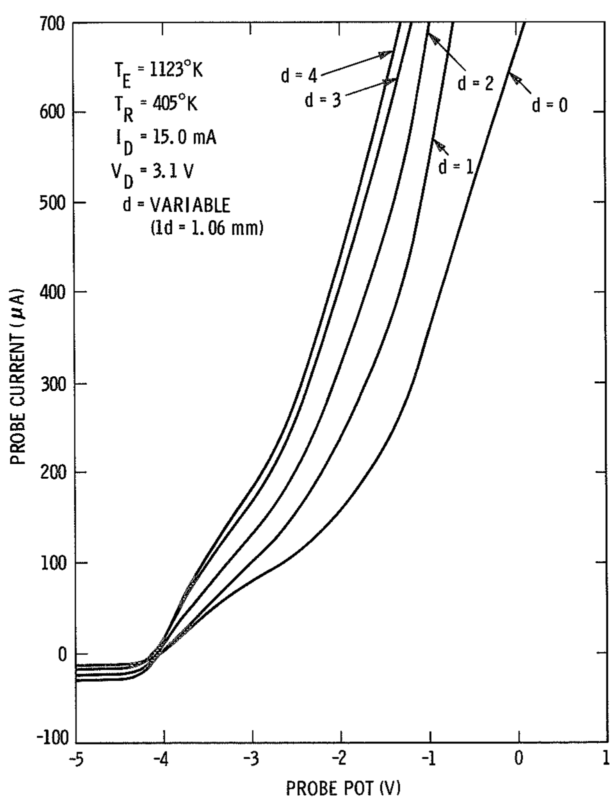

Fig. 9. Probe Characteristics, Ball-of-Fire Mode

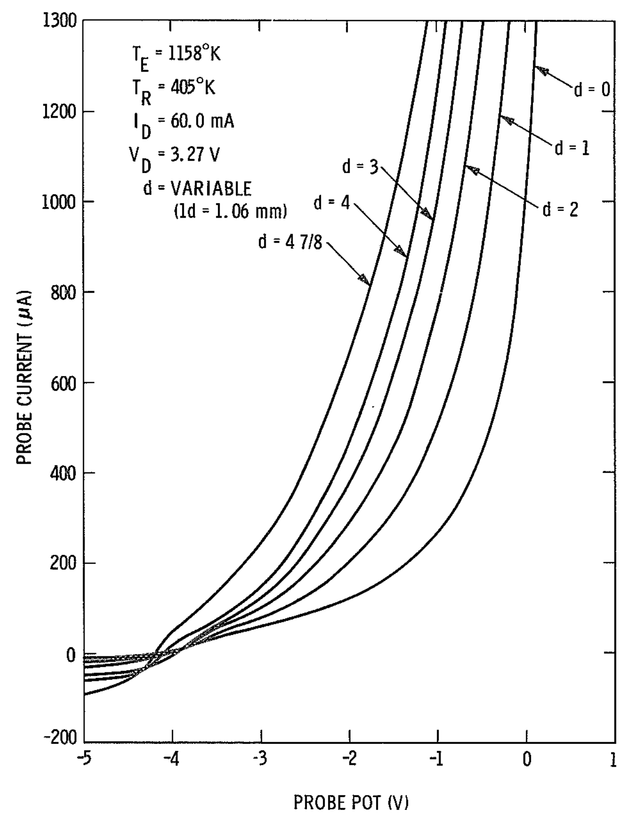

Fig. 10. Probe Characteristics, Plasma Mode

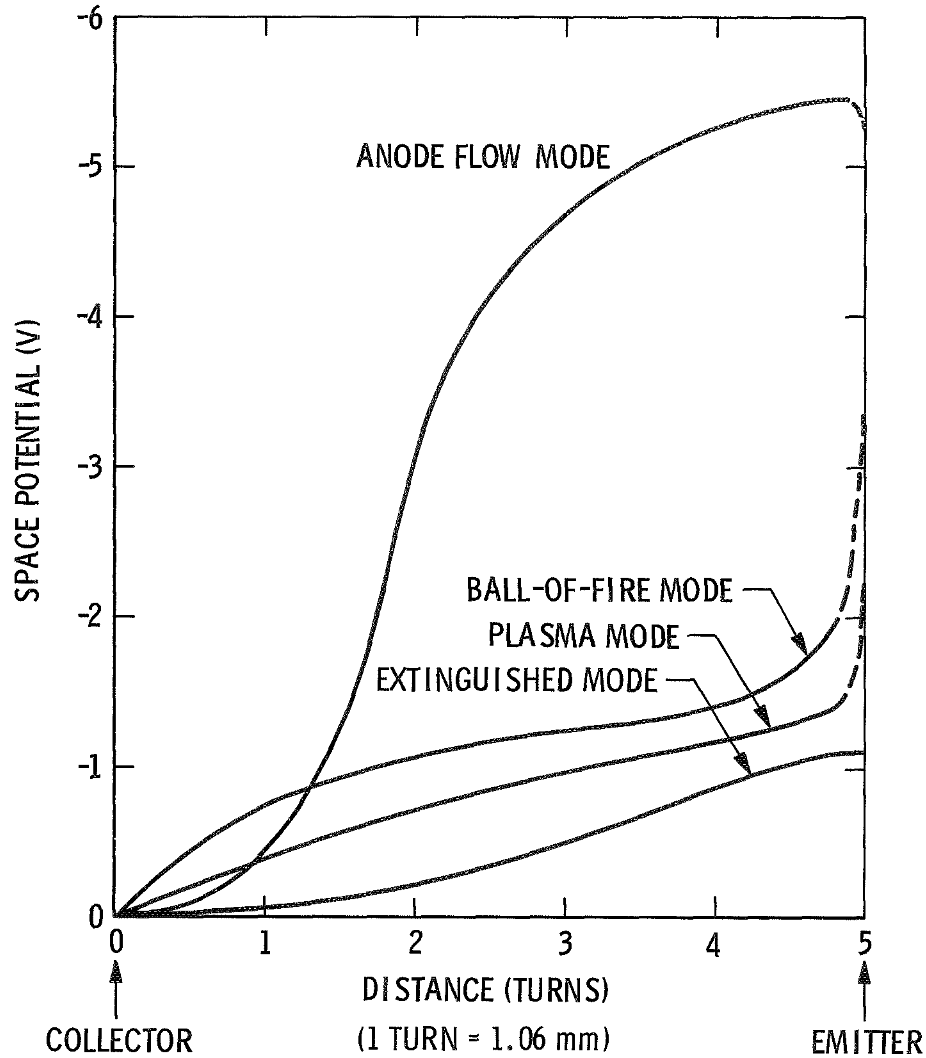

Fig. 11. Space Potential Distribution in Various Modes

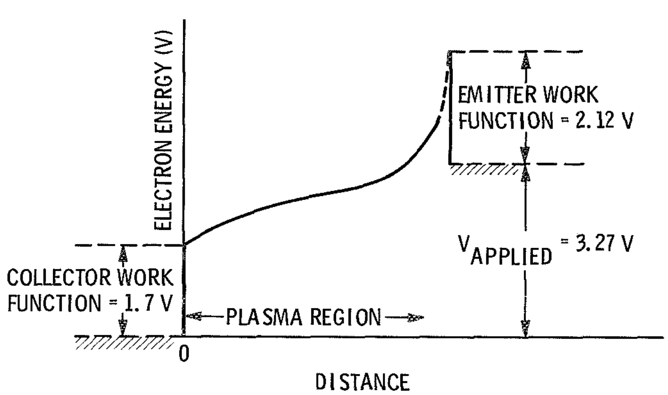

Fig. 12. Electron Energy Diagram, Plasma Mode

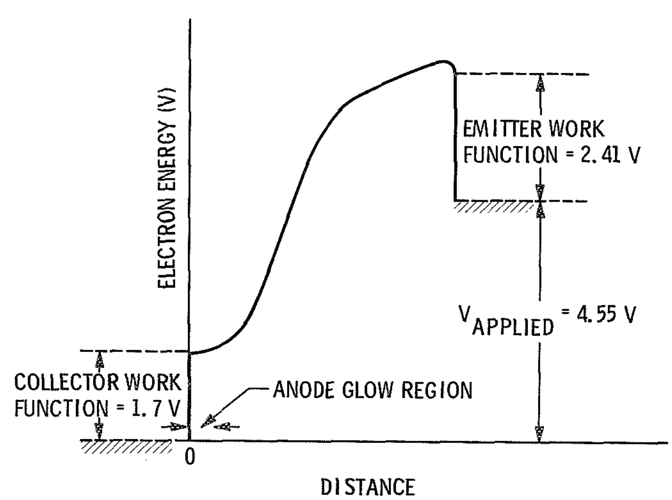

Fig. 13. Electron Energy Diagram, Anode Glow Mode

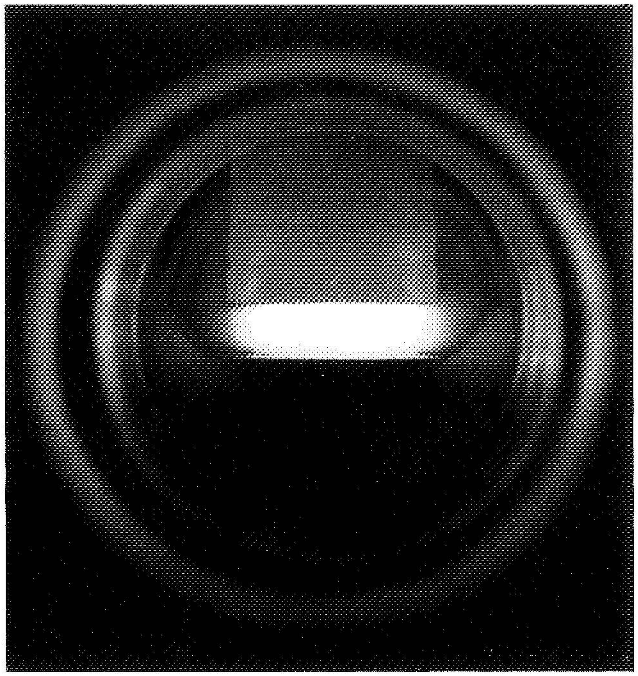

Fig. 14. Cesium Discharge, Plasma Mode

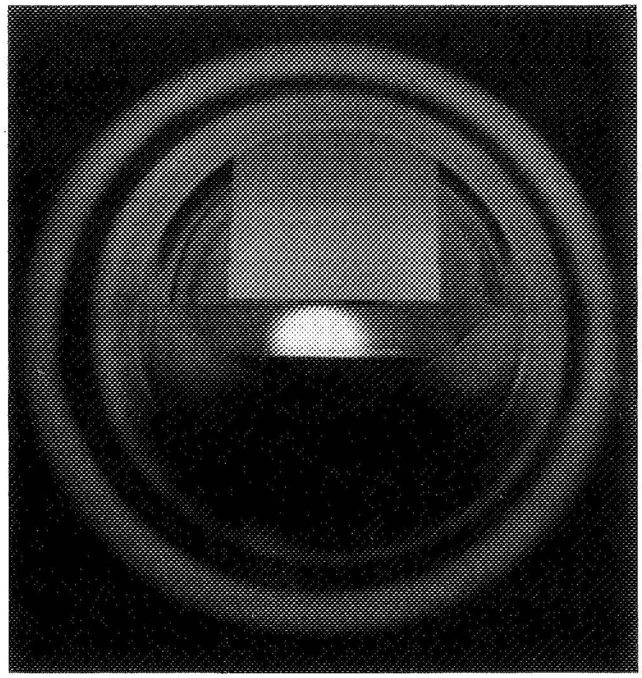

Fig. 15. Cesium Discharge, Ball-of-Fire Mode

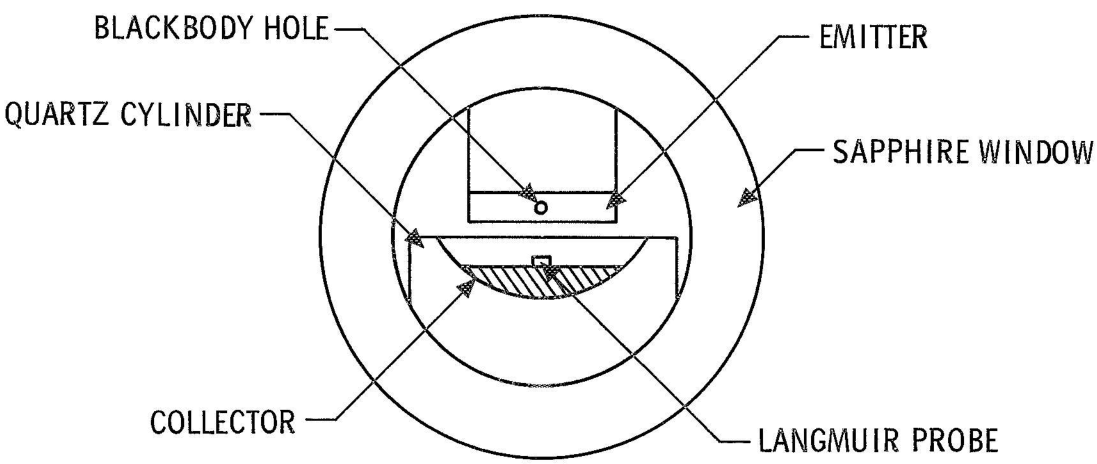

Fig. 16. Schematic Drawing of a View Through Sapphire Window

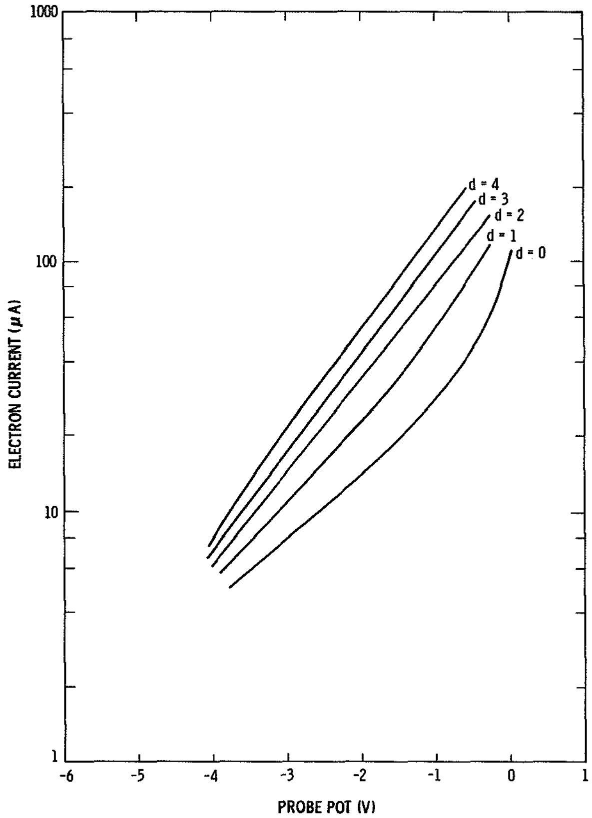

Fig. 17. Semi-Log Probe Characteristics, Plasma Mode

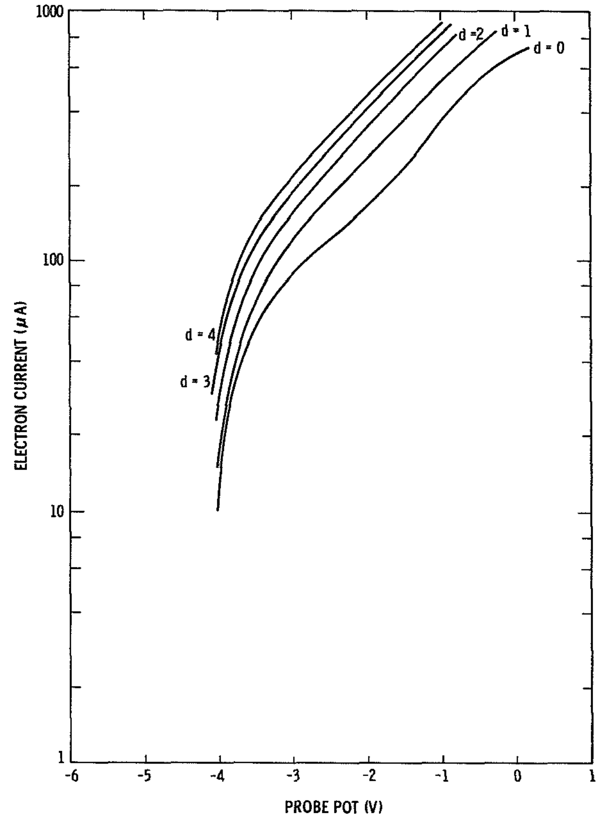

Fig. 18. Semi-Log Probe Characteristics, Ball-of-Fire Mode

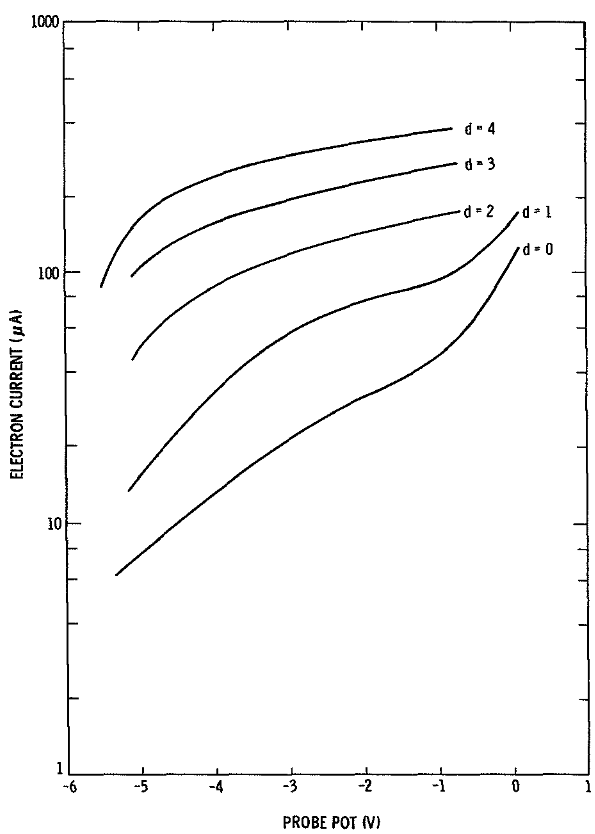

Fig. 19. Semi-Log Probe Characteristics, Anode Glow Mode

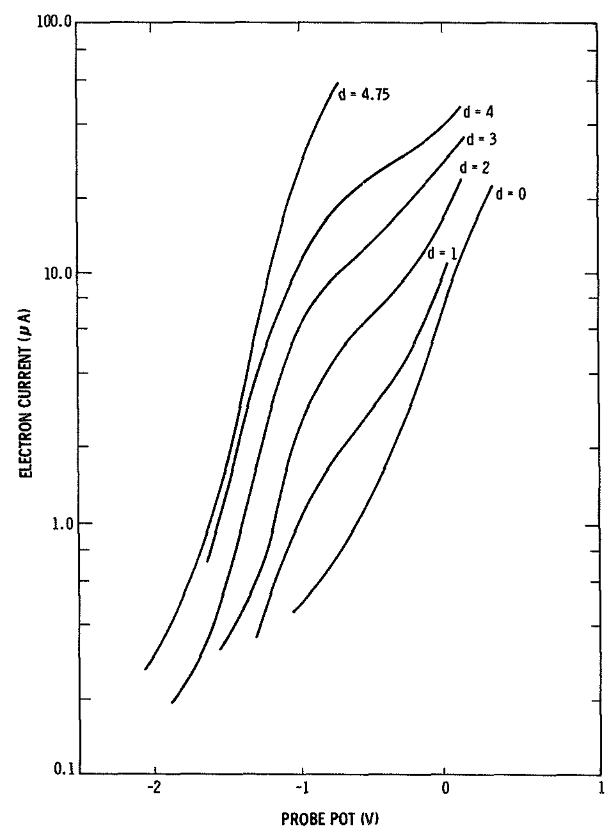

Fig. 20. Semi-Log Probe Characteristics, Extinguished Mode

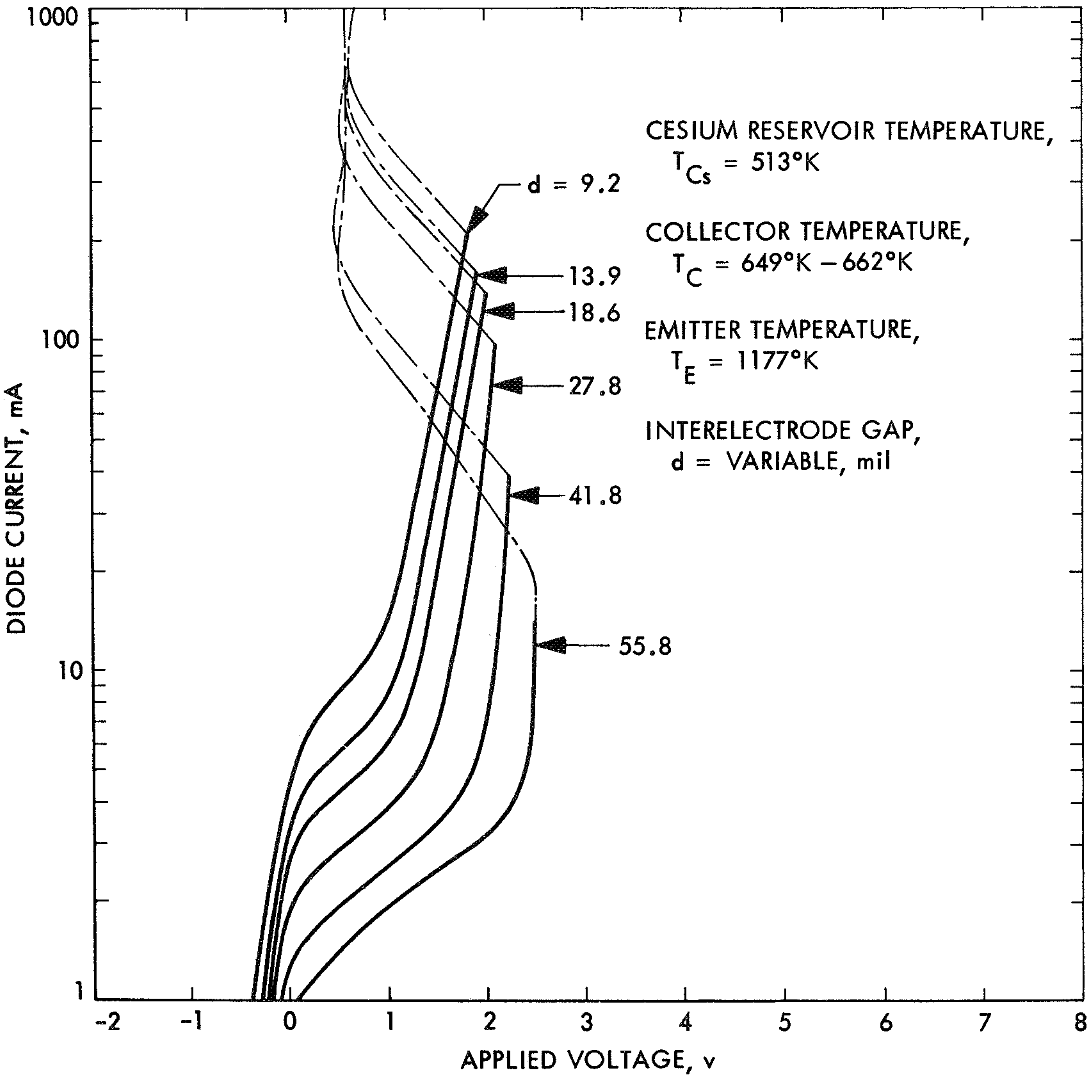

Fig. 21. Volt-Ampere Curves of Variable-Gap Thermionic Converter

NASA — JPL — Coml., L.A., Calif.